Introducing the Greenhouse Effect

EES 3310/5310

Global Climate Change

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Class #4: Monday, Feb. 1 2021

Basic Principles from Friday

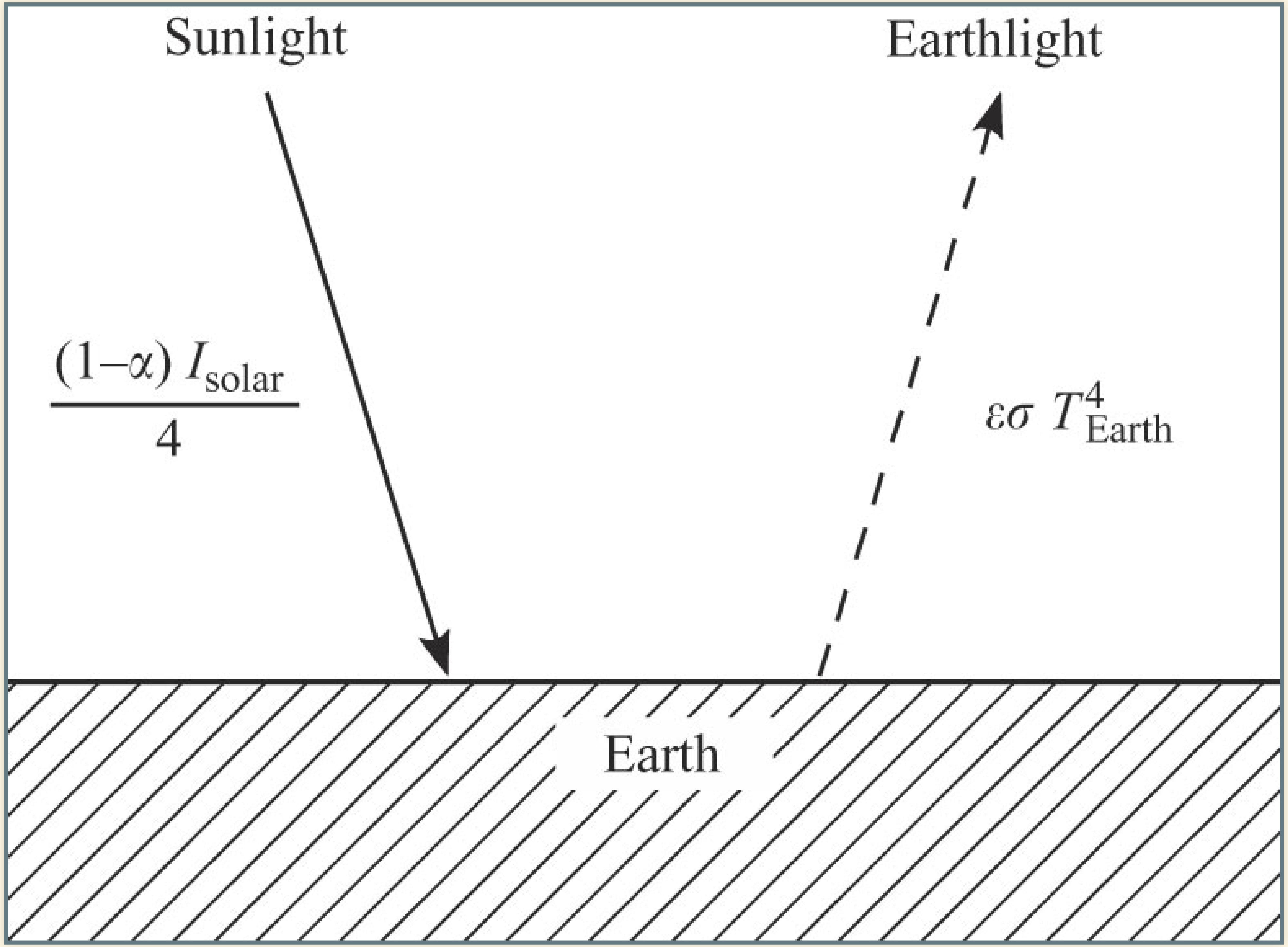
- **Steady temperature means:**
  - $\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$
- **Heat in:**
  - Sunlight (**shortwave**)
  - Does not depend on temperature
- **Heat out:**
  - Emitted radiation (**longwave**)
  - Depends on temperature
- If $\text{Heat}_{\text{out}} \neq \text{Heat}_{\text{in}}$,
  - Temperature rises or falls until

$$\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$$

Processing math: 100%

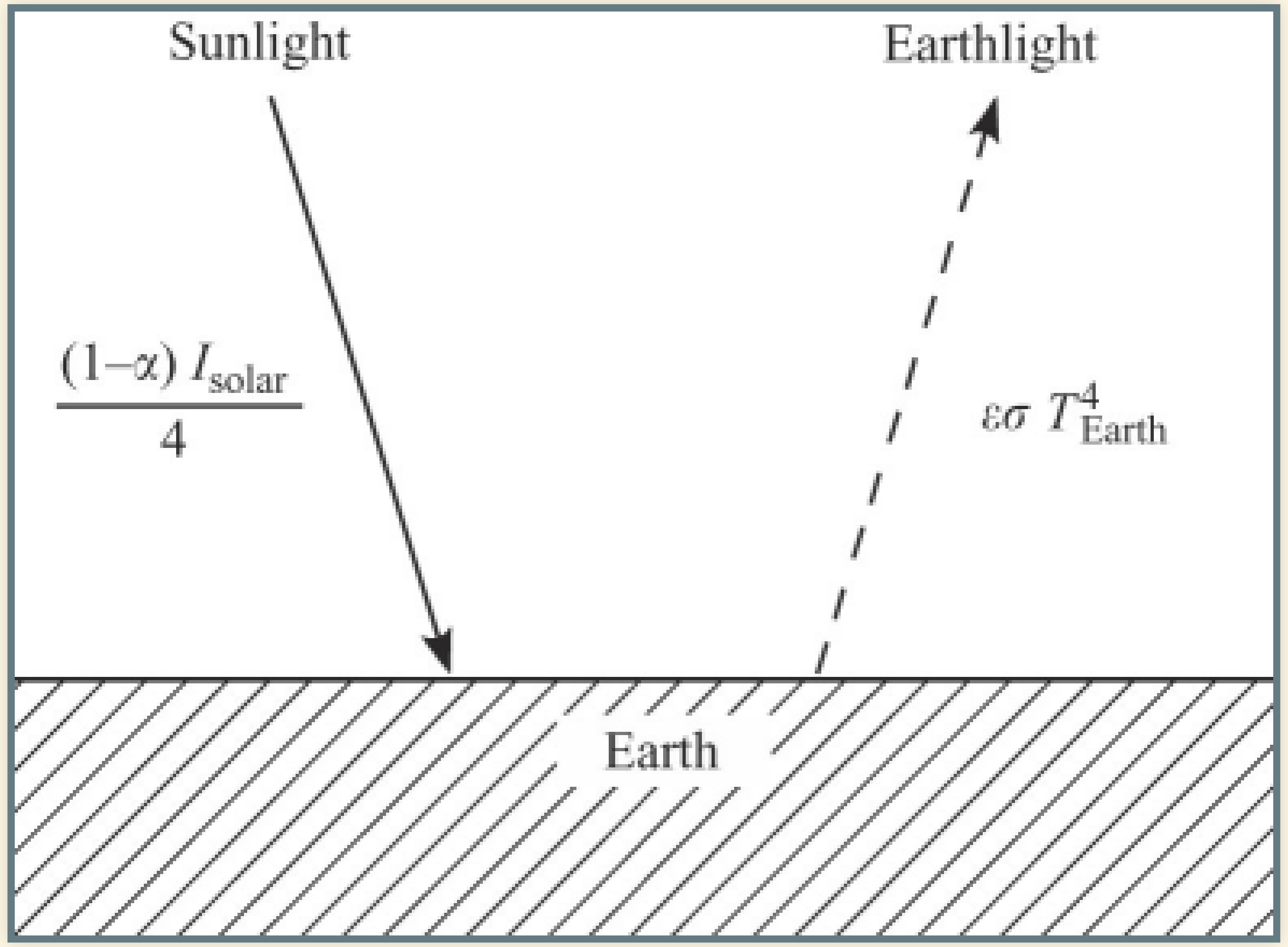
Temperature of the Earth

Bare-Rock Model: No Atmosphere



A subtle point...

- Emissivity ε is fraction absorbed
- Albedo α is fraction reflected
- For an opaque surface, $\alpha + \varepsilon = 1$
- So how is $\alpha = 0.30$ and $\varepsilon = 1.00$?
- α & ε are different for shortwave & longwave.
- Shortwave: $\alpha = 0.30$, $\varepsilon = 0.70$
- Longwave: $\alpha = 0.00$, $\varepsilon = 1.00$



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Temperature of Earth (Bare Rock Model)

1. $F_{\text{out}} = F_{\text{in}}$ (Heat flux balances)
2. On average,

$$F_{\text{in}} = \frac{(1-\alpha)}{4} I_{\text{solar}}$$

3. $F_{\text{out}} = \varepsilon \sigma T^4$.
4. Solve for T:

$$T = \sqrt[4]{\frac{(1-\alpha) I_{\text{solar}}}{4 \varepsilon \sigma}}$$

$$\begin{aligned}
I_{\text{solar}} &= 1350\ \mathrm{W/m^2} \\
\alpha &= 0.30 \\
\varepsilon &= 1 \\
\sigma &= 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}} \\
T &= 254\ \mathrm{K} = -19\,^\circ\mathrm{C} = -2\,^\circ\mathrm{F}
\end{aligned}$$

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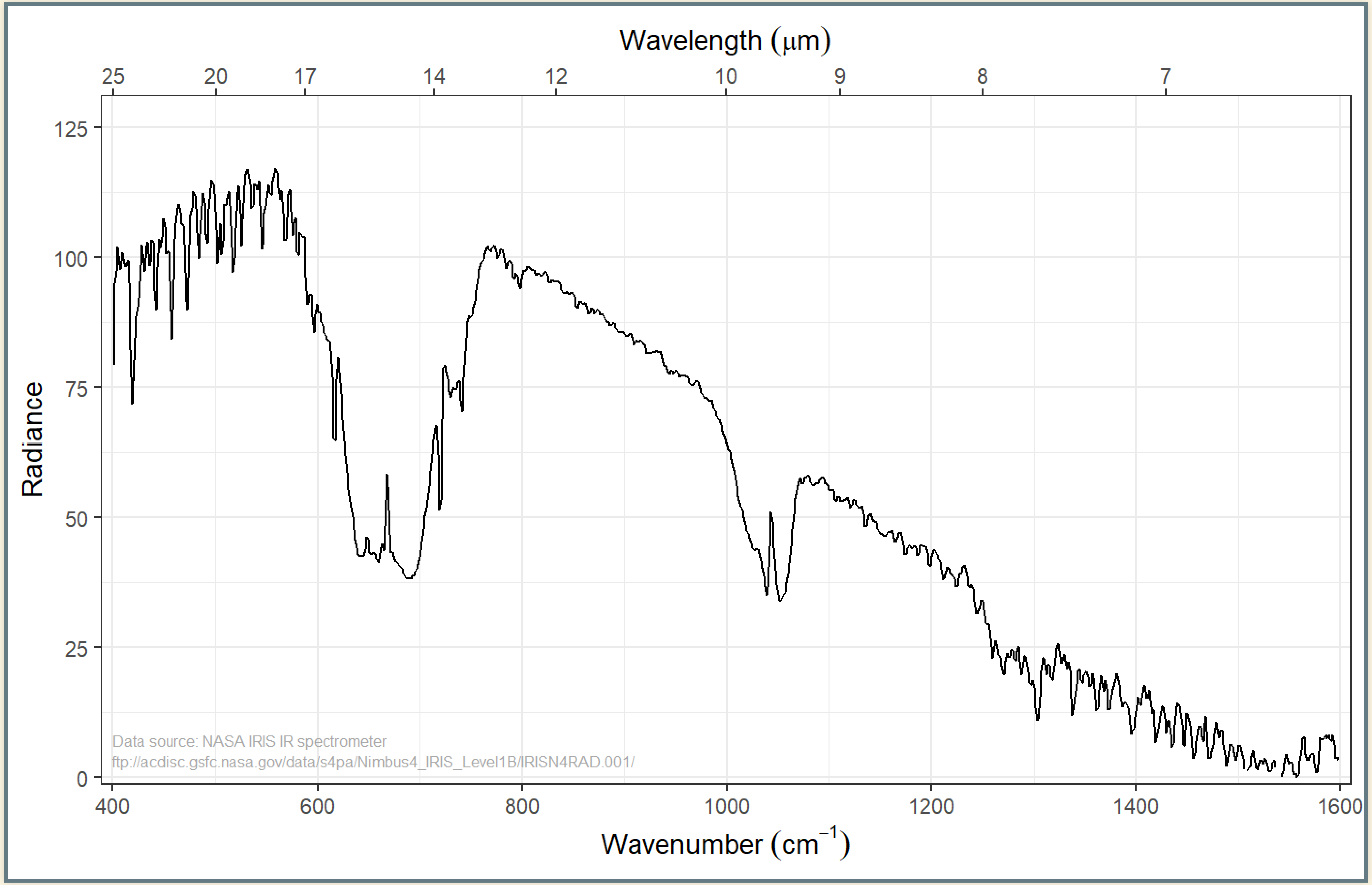
Terrestrial Planets

	Earth	**Mars**	**Venus**
Distance from sun	1 AU	1.5 AU	0.72 AU
$1/\text{Distance}^2$	1.00	0.44	1.9
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
Albedo	0.30	0.17	0.71
$T_{\text{bare rock}}$	$254\ \mathrm{K}\ (-2\,^{\circ}\mathrm{F})$	$216\ \mathrm{K}\ (-70\,^{\circ}\mathrm{F})$	$240\ \mathrm{K}\ (-27\,^{\circ}\mathrm{F})$
T_{surface}	$295\ \mathrm{K}\ (71\,^{\circ}\mathrm{F})$	$240\ \mathrm{K}\ (-28\,^{\circ}\mathrm{F})$	$700\ \mathrm{K}\ (800\,^{\circ}\mathrm{F})$
Δ_T	$41\ \mathrm{K}\ (74\,^{\circ}\mathrm{F})$	$24\ \mathrm{K}\ (42\,^{\circ}\mathrm{F})$	$460\ \mathrm{K}\ (828\,^{\circ}\mathrm{F})$

Oops! We forgot the atmosphere!



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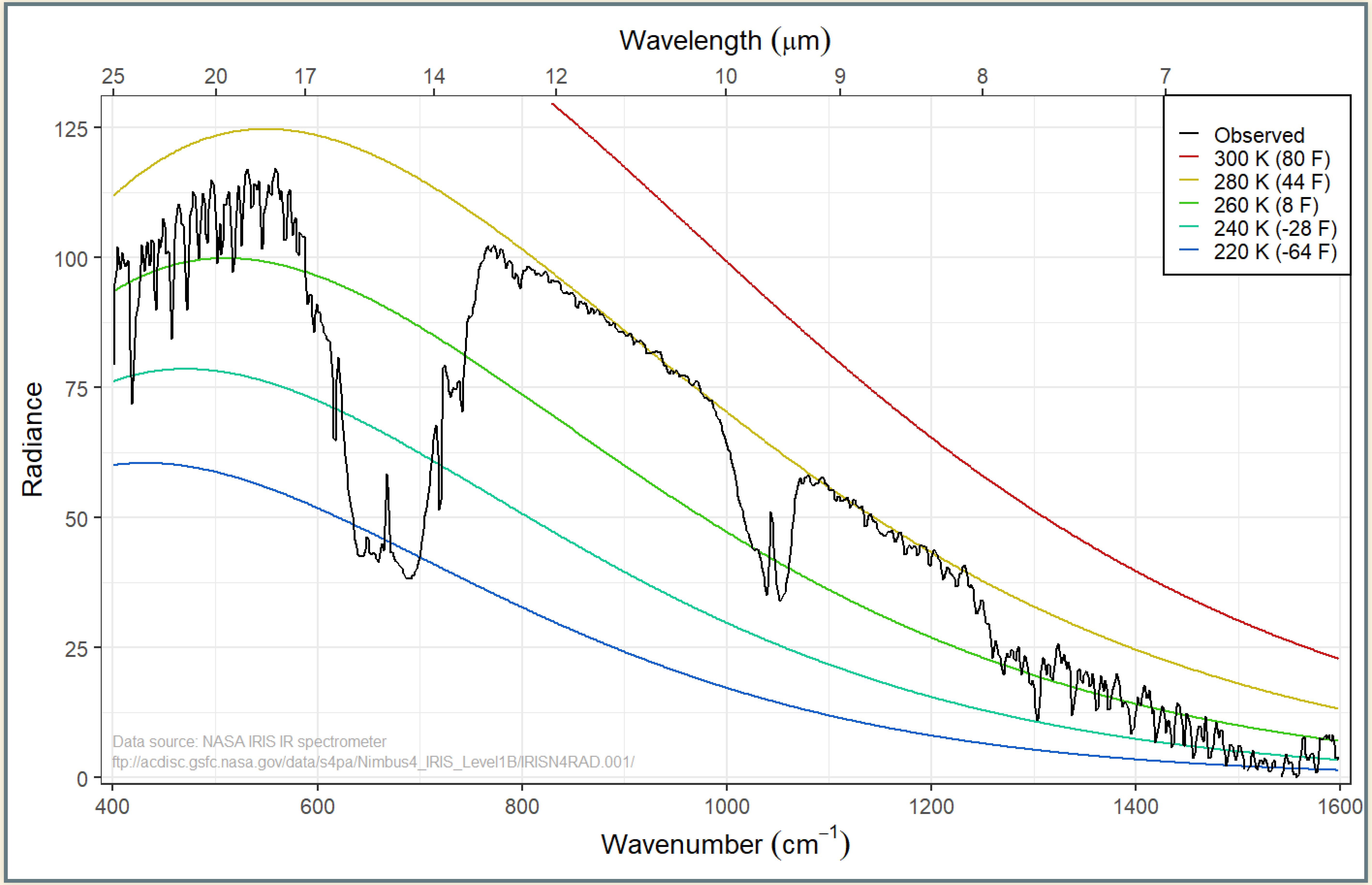
Does Earth look like a blackbody?



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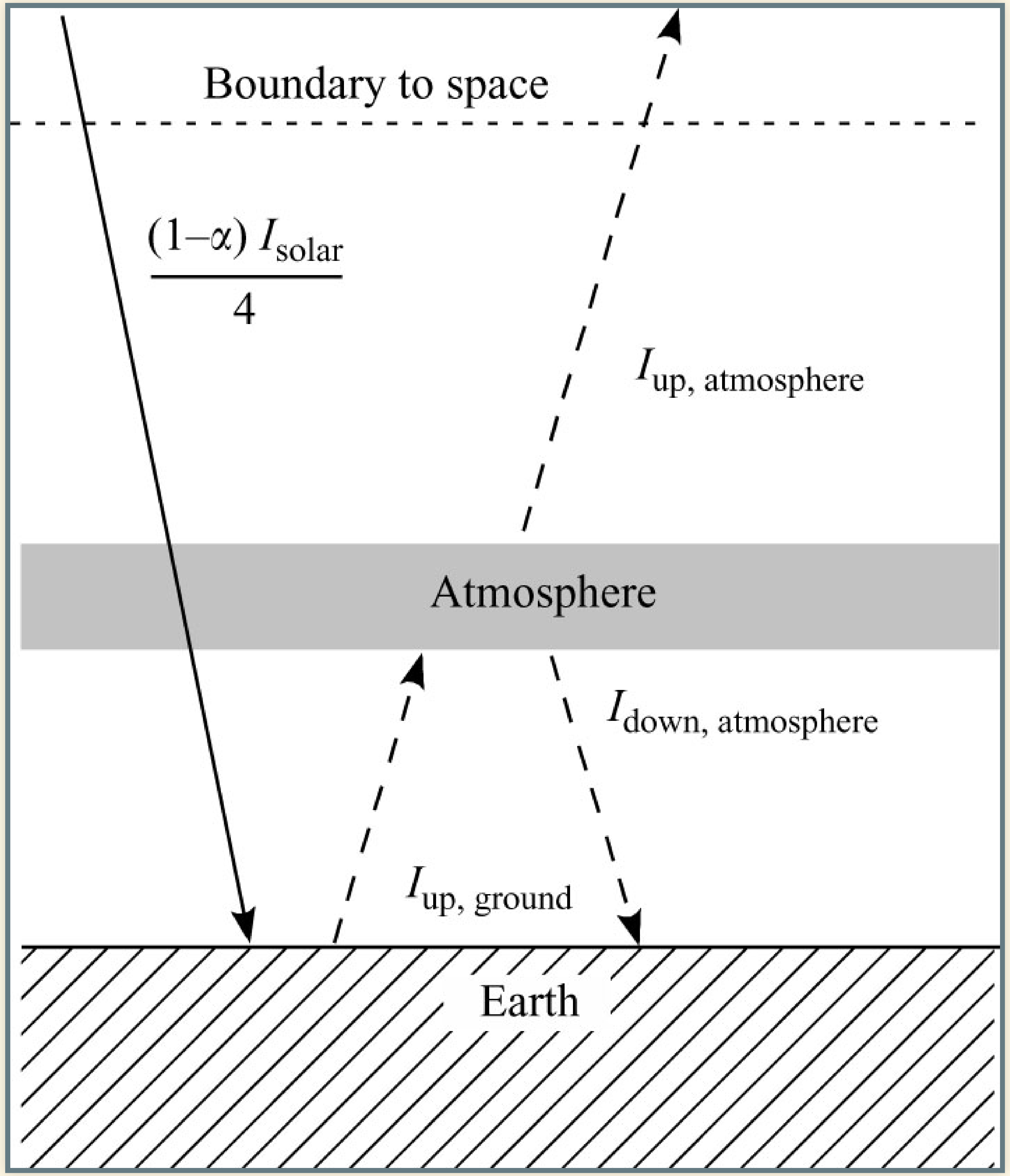
One-Layer Model of the Greenhouse Effect

Layer Model



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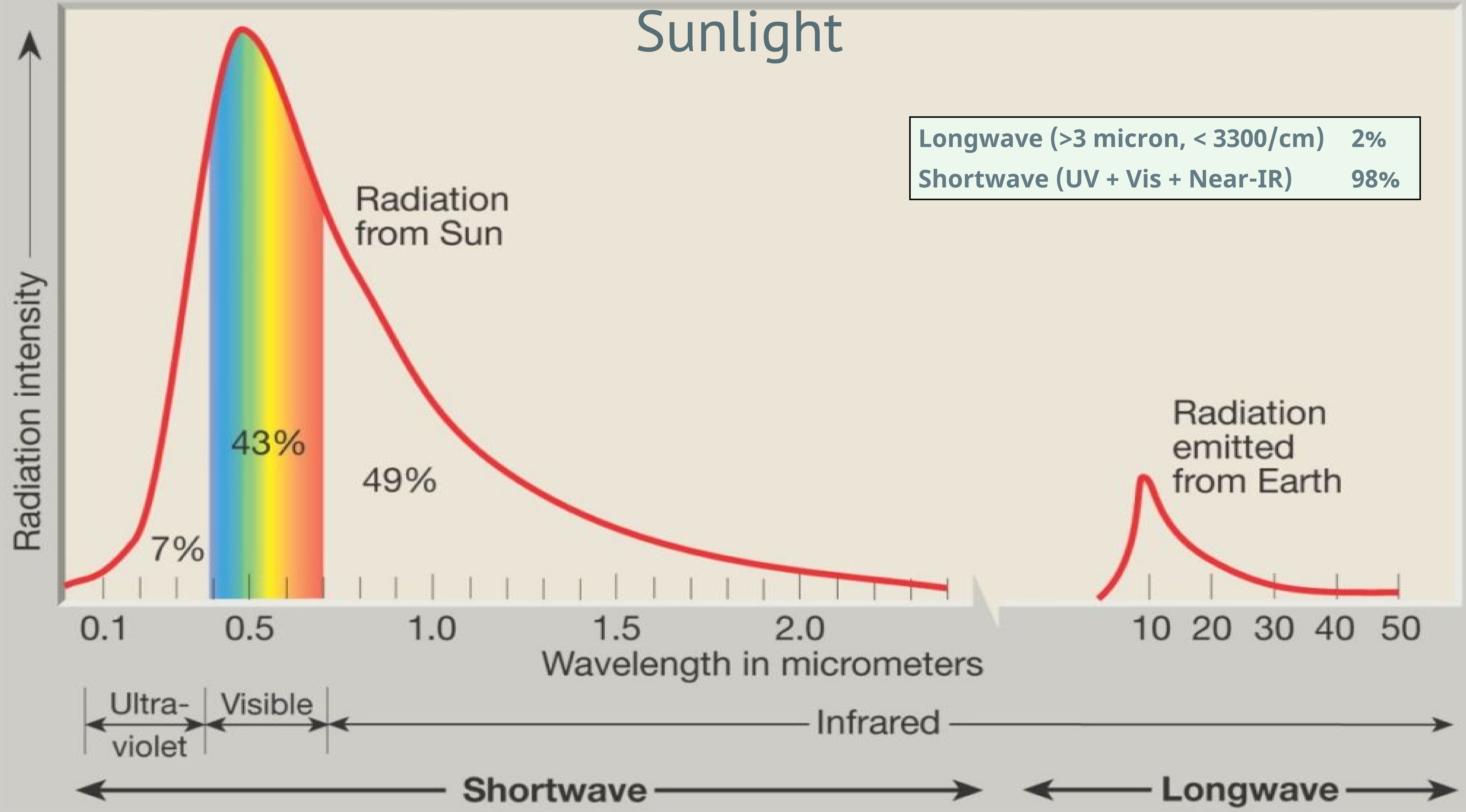
Sunlight

Longwave (>3 micron, < 3300/cm)	2%
Shortwave (UV + Vis + Near-IR)	98%



Atmosphere

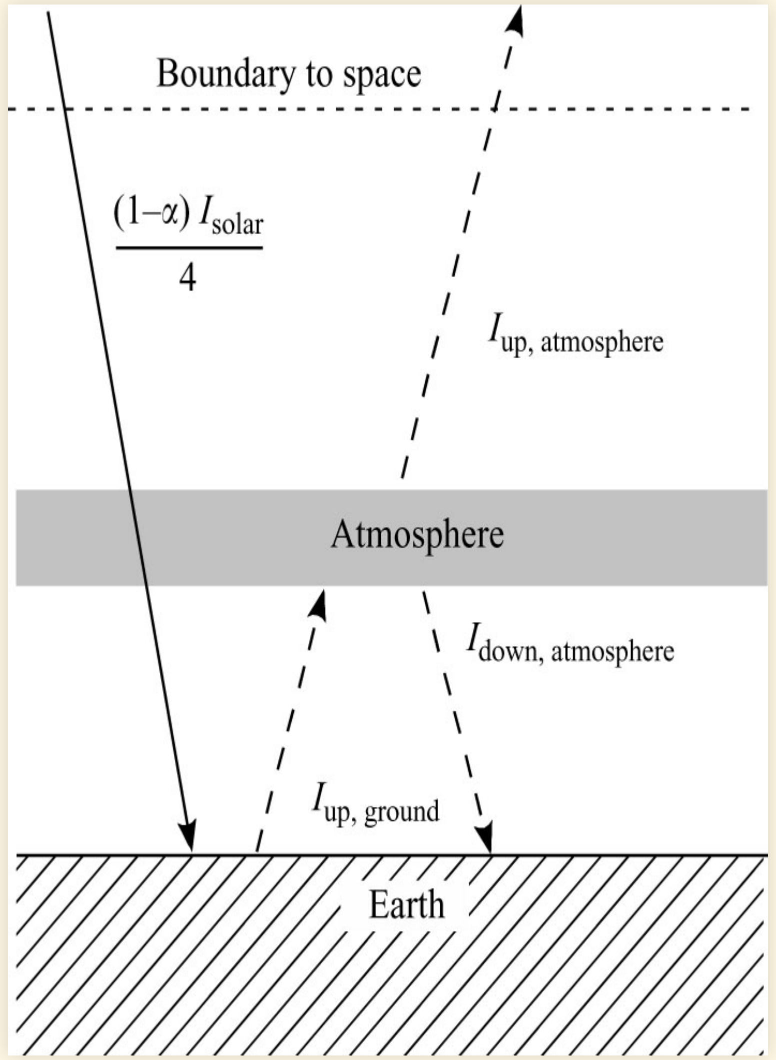
Make **simplifying assumptions**:

- Perfectly **transparent** to **shortwave** light
  - Like a pane of glass: $\varepsilon = 0$
- Perfectly **opaque** to **longwave** light
  - Like a blackbody: $\varepsilon = 1$

Anything that
transmits most shortwave
and
absorbs most longwave
is a greenhouse gas

Balance of energy for earth system

- Always start analyzing from the top down
  - Look at energy balance at the boundary to space, above the top of the atmosphere.



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Balance of energy for earth system

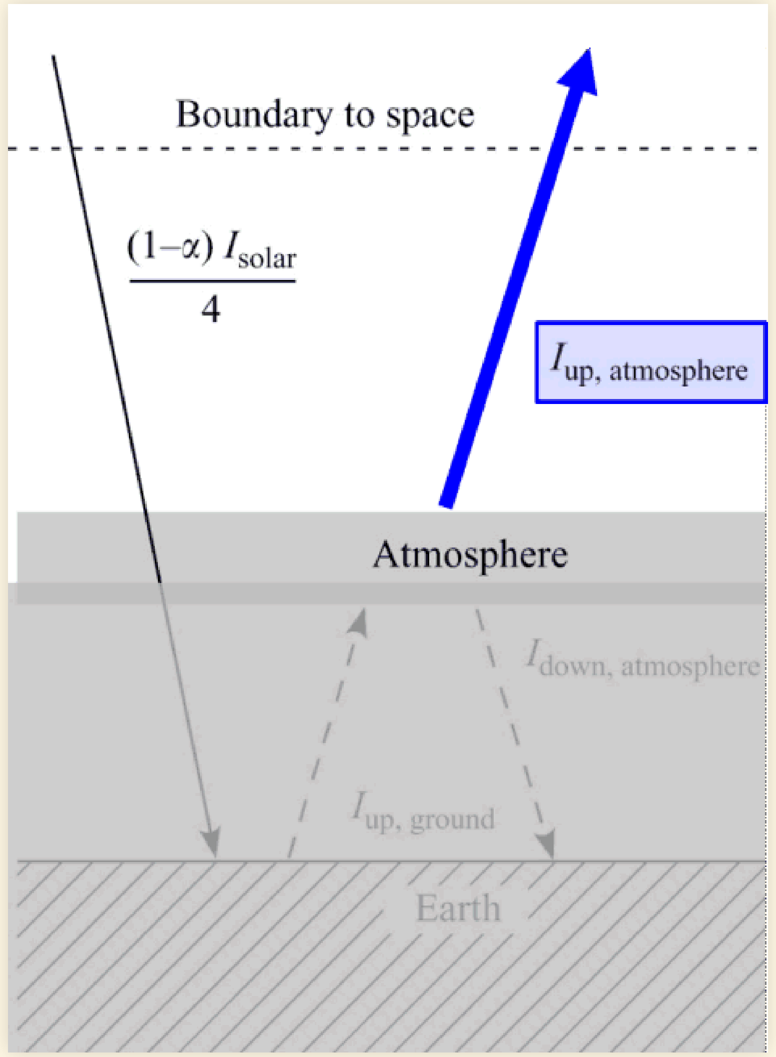
- At top of atmosphere: $F_{\text{out}} = F_{\text{in}}$

$$I_{\text{up, atmos}} = I_{\text{in}} \quad \text{(intensity of absorbed sunlight)}$$

$$\varepsilon \sigma T^4_{\text{atmos}} = \frac{(1-\alpha) I_{\text{solar}}}{4}$$

- Aha! We can find T_{atmos}!

$$T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\, I_{\text{solar}}}{4 \varepsilon \sigma}}$$



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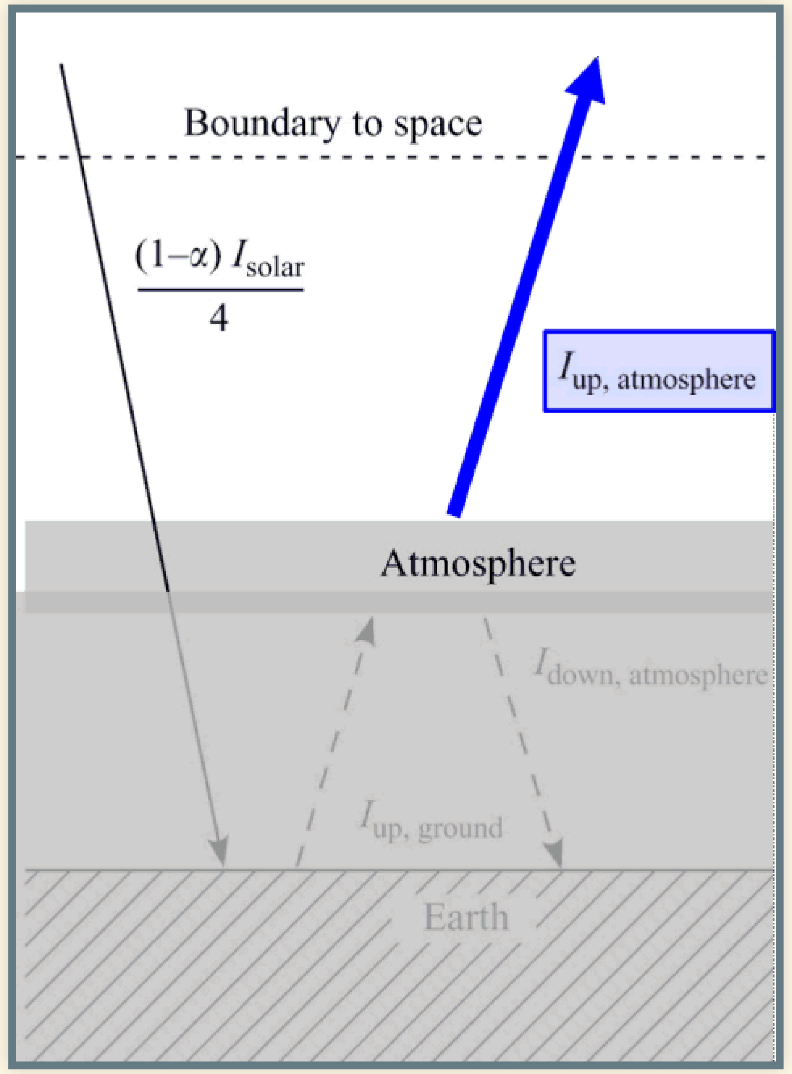
Balance of energy for earth system

$$T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\,I_{\text{solar}}}{4\varepsilon\sigma}}$$



- Just like bare rock model!
- We call this the **skin temperature**

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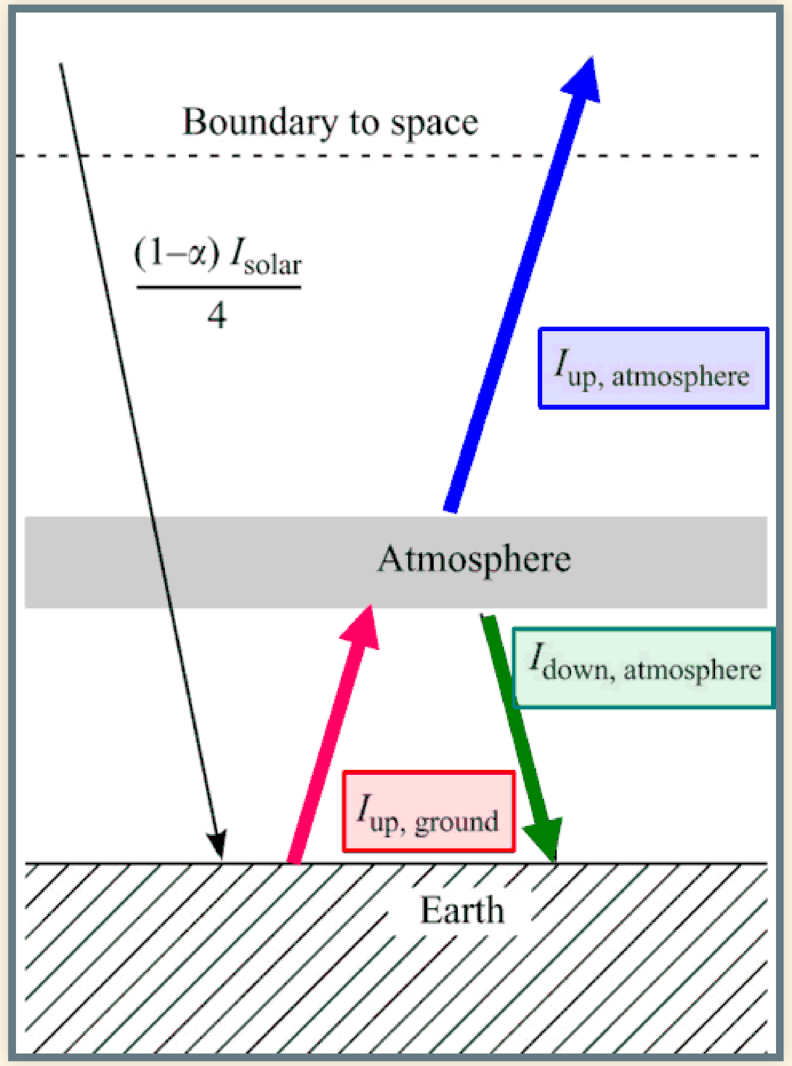
Balance of energy for atmosphere

Atmosphere: $\mathrm{Heat}_{\mathrm{in}} = \mathrm{Heat}_{\mathrm{out}}$

$$I_{\mathrm{up,ground}} = I_{\mathrm{up,atm}} + I_{\mathrm{down,atm}}$$



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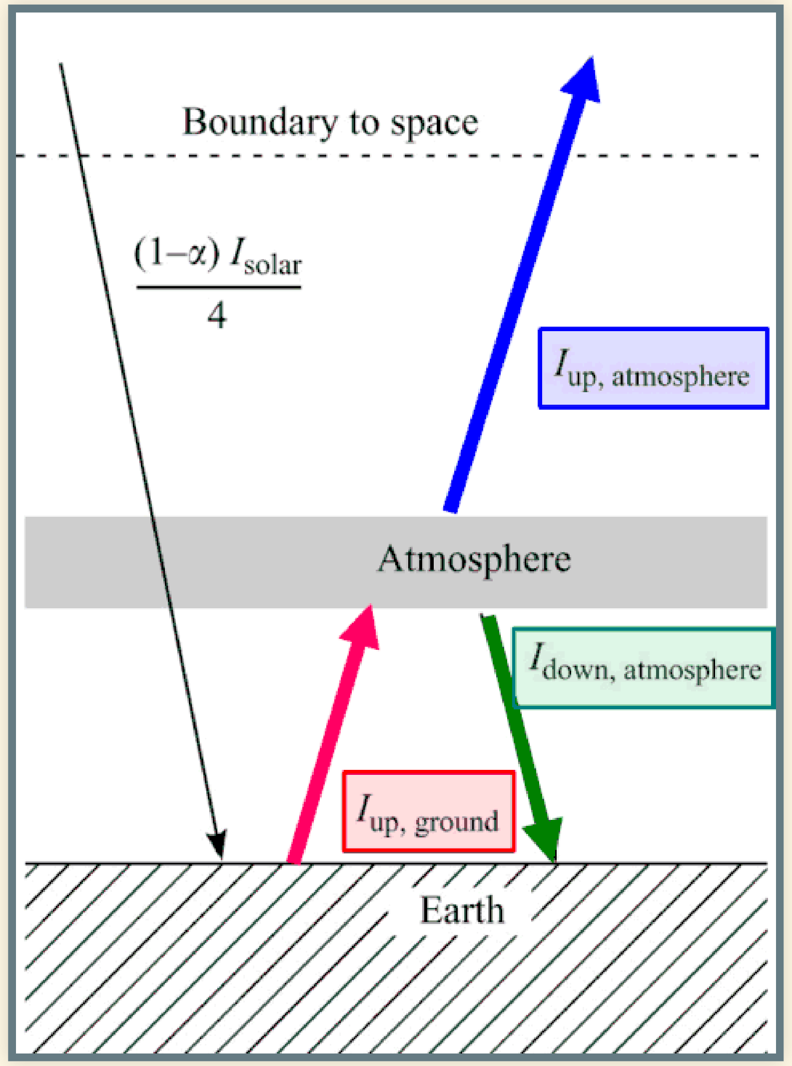
Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4$$



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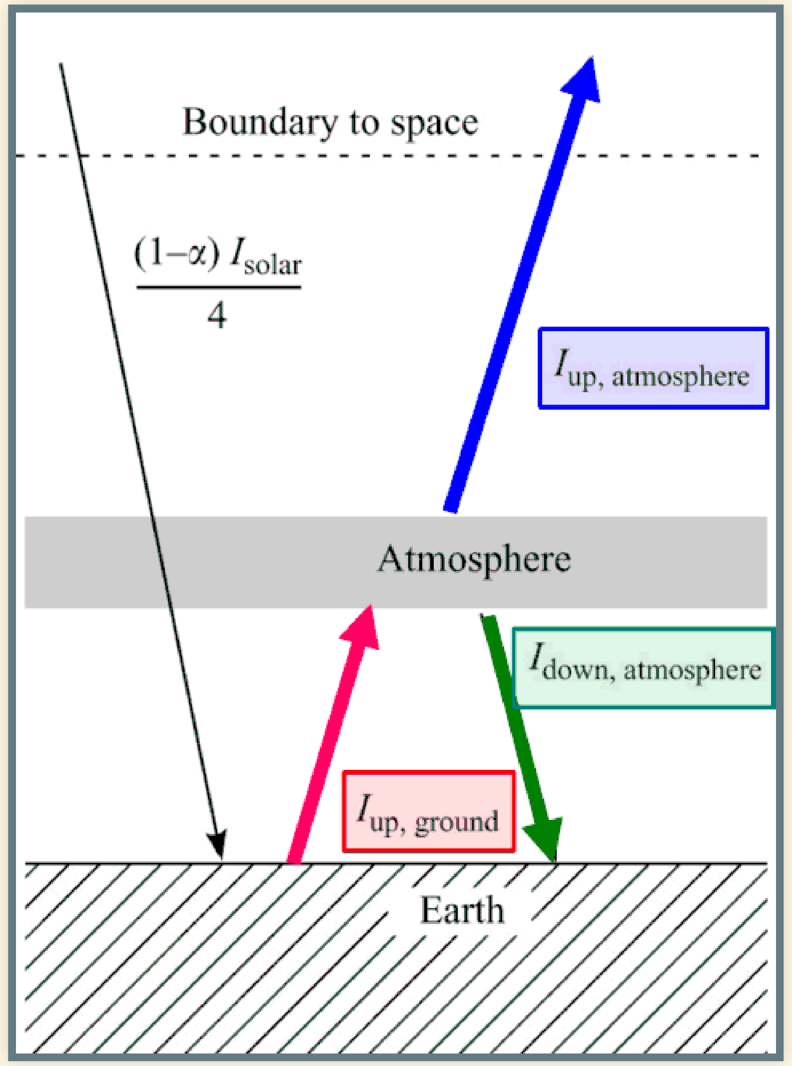
Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T^4_{\text{atm}}$$

$$I_{\text{up,ground}} = \varepsilon\sigma T^4_{\text{ground}}$$



Balance of energy for atmosphere

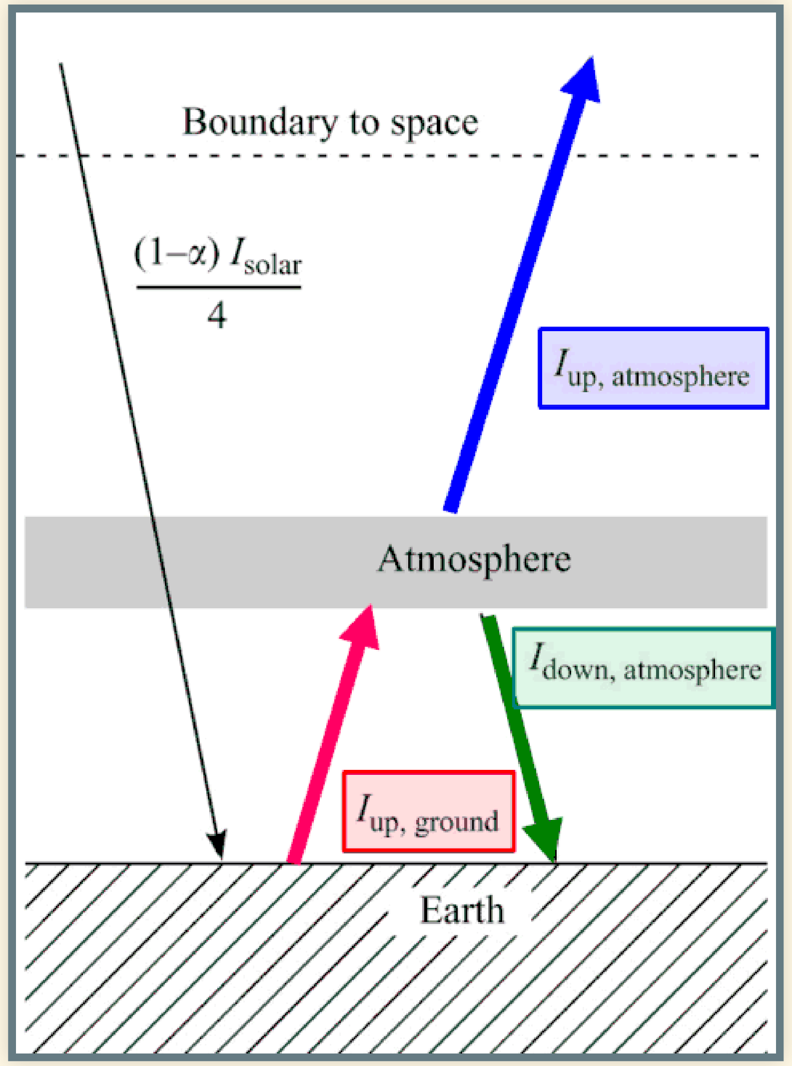
Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4$$

$$I_{\text{up,ground}} = \varepsilon\sigma T_{\text{ground}}^4$$

$$\varepsilon\sigma T_{\text{ground}}^4 = 2\varepsilon\sigma T_{\text{atm}}^4$$



Principles:

- Start at the top.
- For each layer, $\text{Heat}_{\text{out, up}} = \text{Heat}_{\text{out, down}}$
- Each layer balances $\text{Heat}_{\text{in, total}} = \text{Heat}_{\text{out, total}}$
    - Each layer has uniform temperature:
        - The top and bottom of the layer have the same temperature.
        - So the intensity emitted from the top and bottom is the same.
- The bottom layer of the atmosphere tells us $\text{Heat}_{\text{up, ground}}$
- Get ground temperature from $\text{Heat}_{\text{up, ground}}$

Processing math: 100%

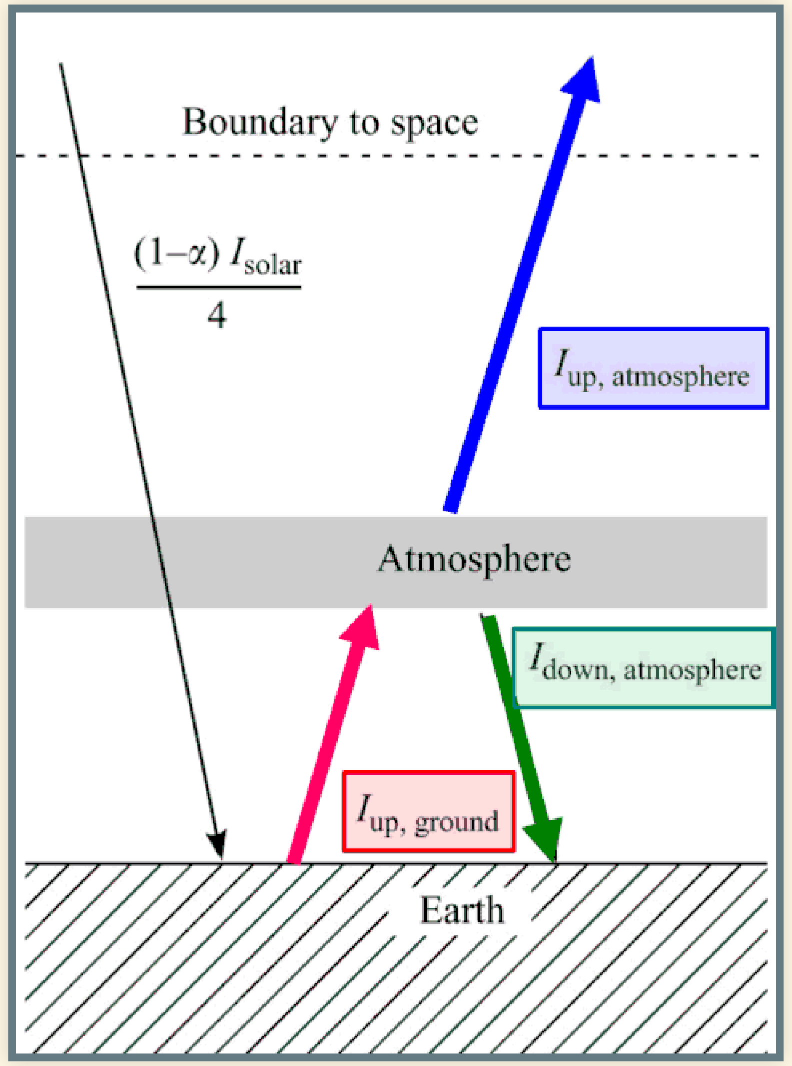
Finish the problem

$$\varepsilon\sigma T_{\text{ground}}^{4} = 2\varepsilon\sigma T_{\text{atm}}^{4}$$

$$T_{\text{ground}}^{4} = 2T_{\text{atm}}^{4}$$

$$T_{\text{ground}} = \sqrt[4]{2}\,T_{\text{atm}}$$

$$= 1.19T_{\text{atm}}$$



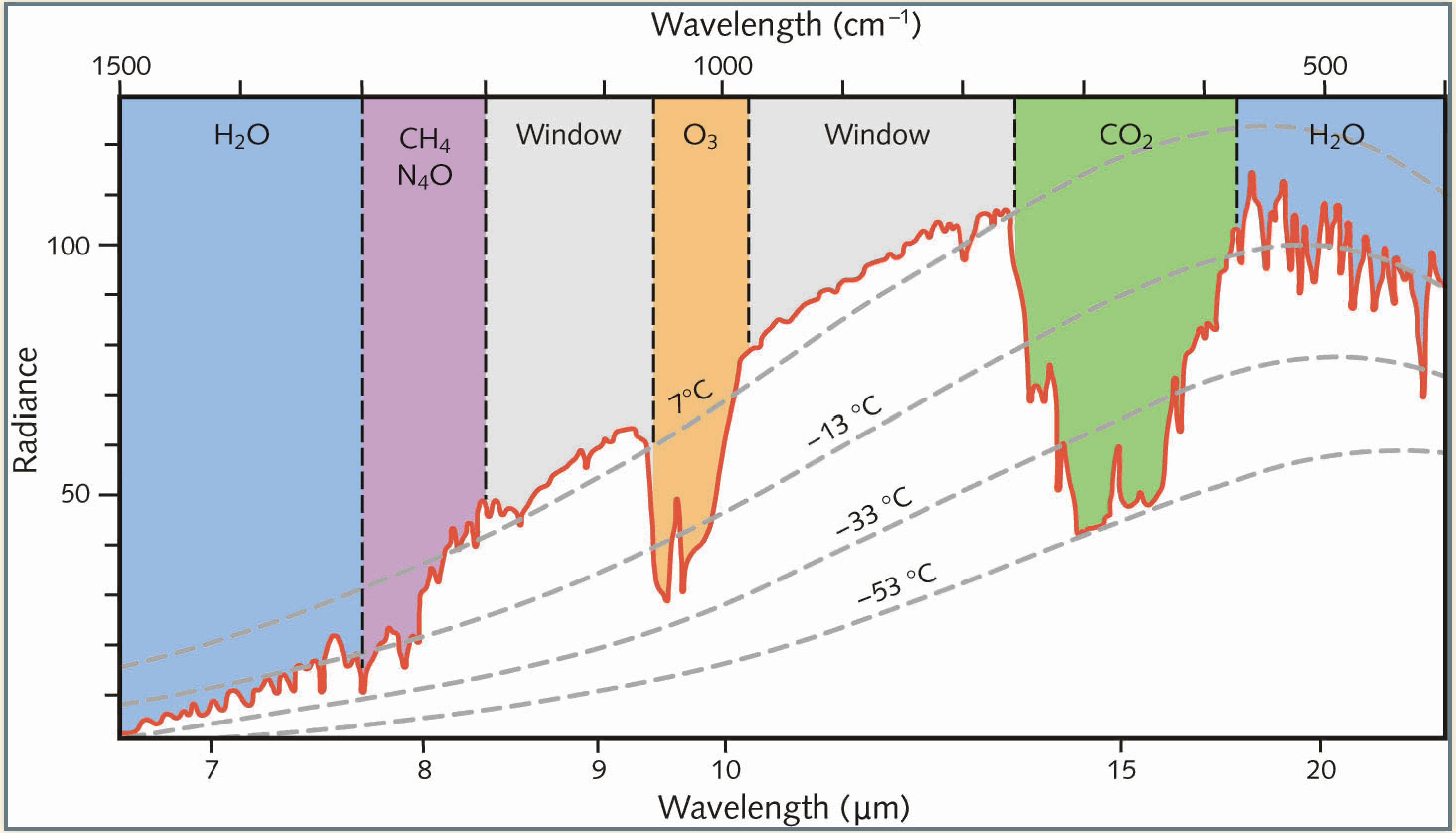
- Skin temp: $T_{\text{atm}} = T_{\text{skin}} = T_{\text{bare rock}} = 254\ K$
- Ground temp (1-layer): $T_{\text{ground}} = \sqrt[4]{2}T_{\text{atm}} = 302\ K$
- Difference: $\text{Greenhouse effect} = 48\ K$

Note: These numbers are slightly different from what's in the book. Don't worry about that.

Processing math: 100%

Greenhouse Gases

Greenhouse Gases



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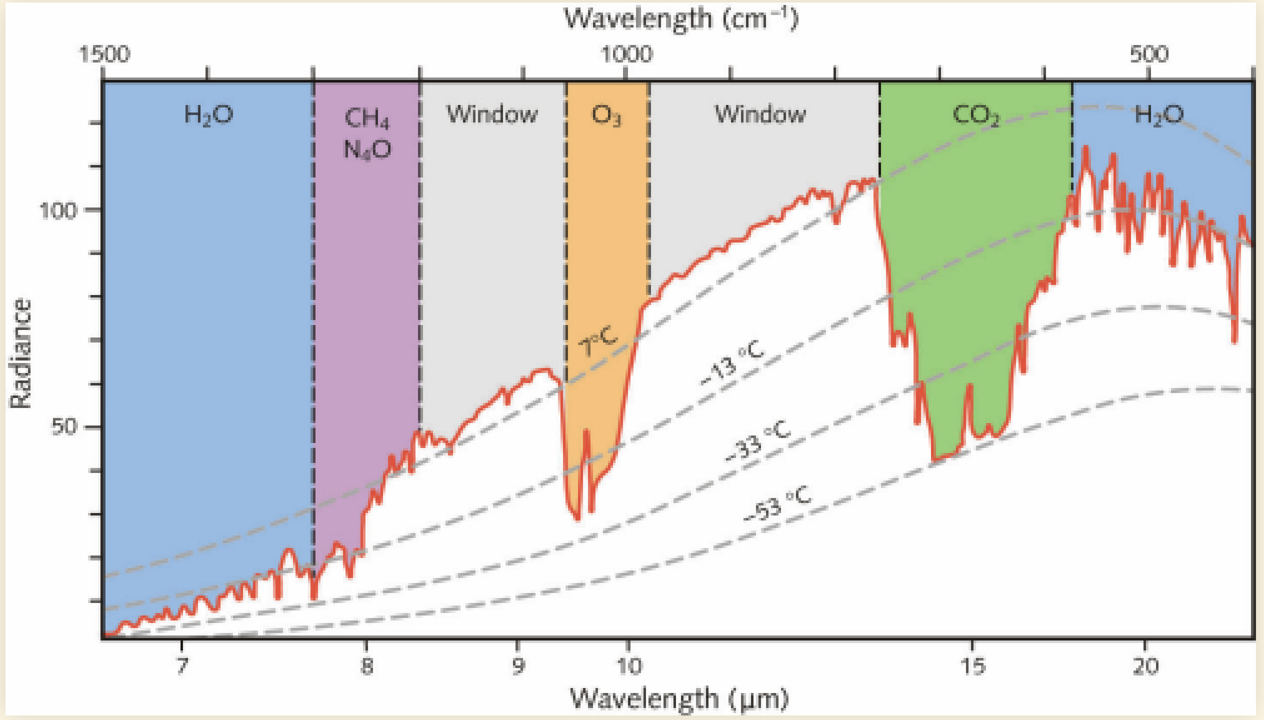
Greenhouse Gases



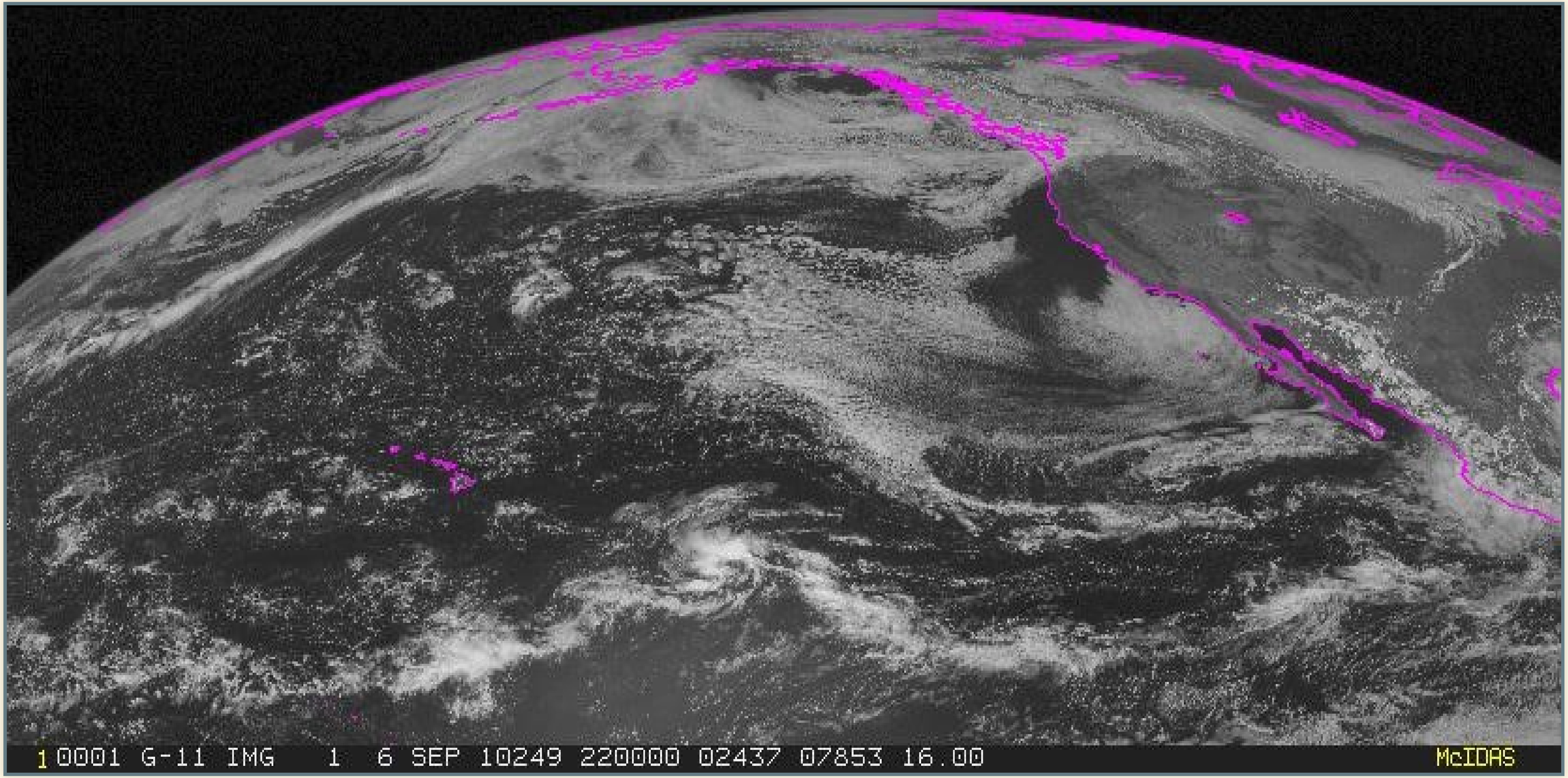
- Brightness: Stefan-Boltzmann law:
  - $I = \varepsilon\sigma T^4$
  - $\varepsilon = 1$

- Brighter = Hotter
- Hotter = closer to ground
  - Satellite can see through atmosphere to low altitude (hot, bright) in “window” region.
  - Satellite can see to middle-troposphere (cold, dimmer) in “water vapor” region
  - Satellite can’t see past top of troposphere (very cold, very dim) in CO_2 region.

Processing math: 100%

Earth Seen by Satellites

Visible



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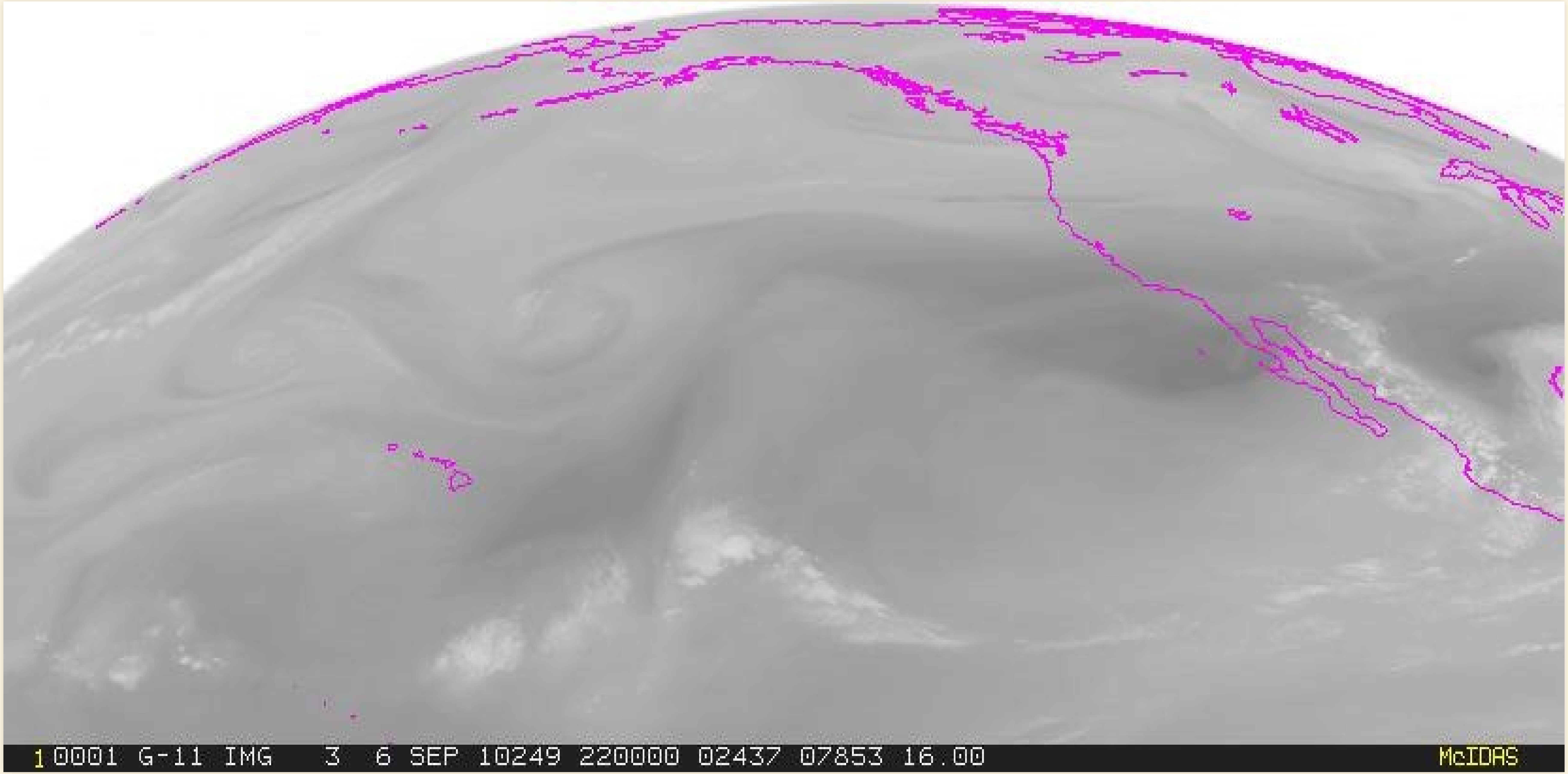
6.8 μm (Water Vapor)



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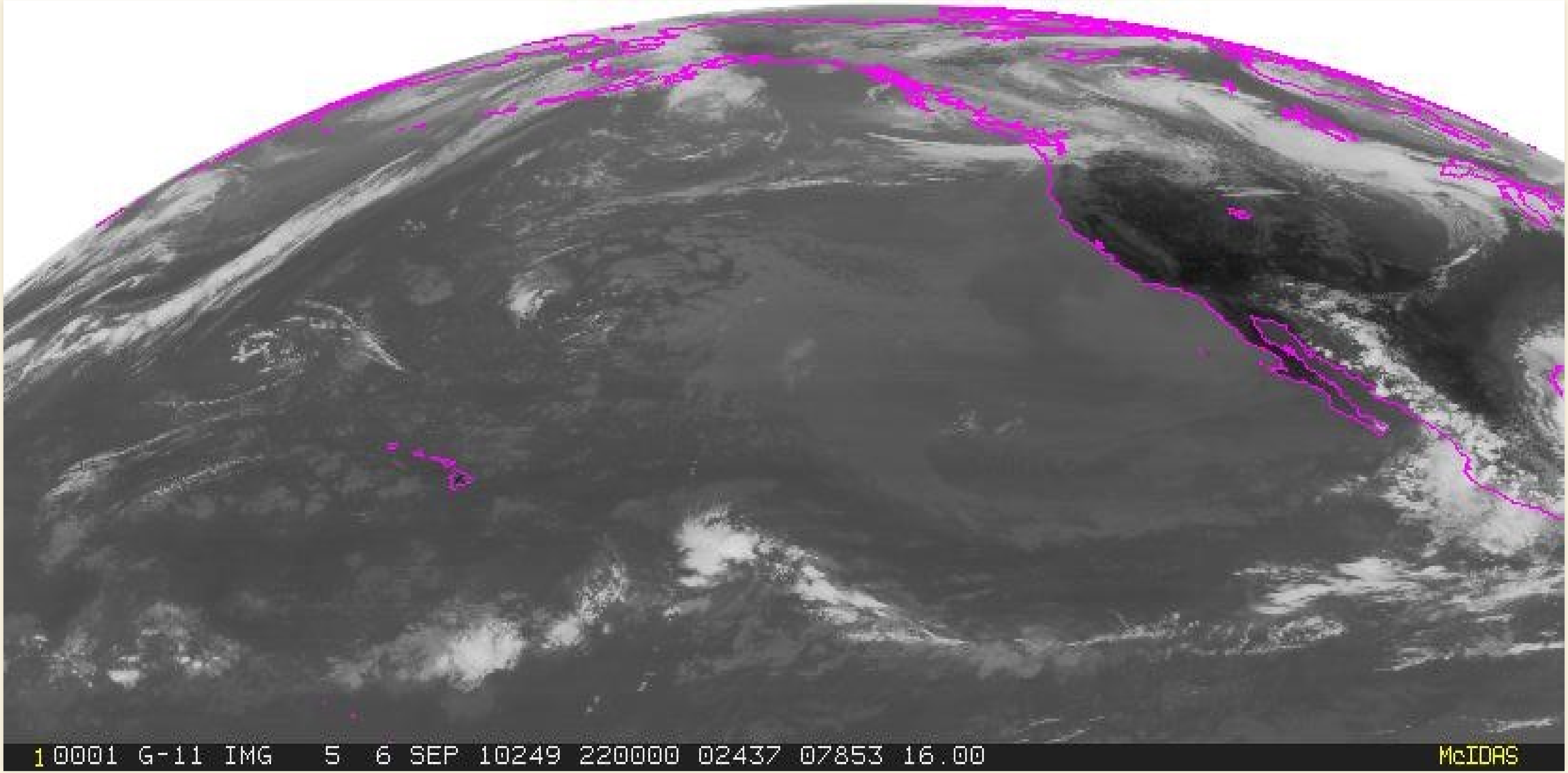
12.0 μm (Window)



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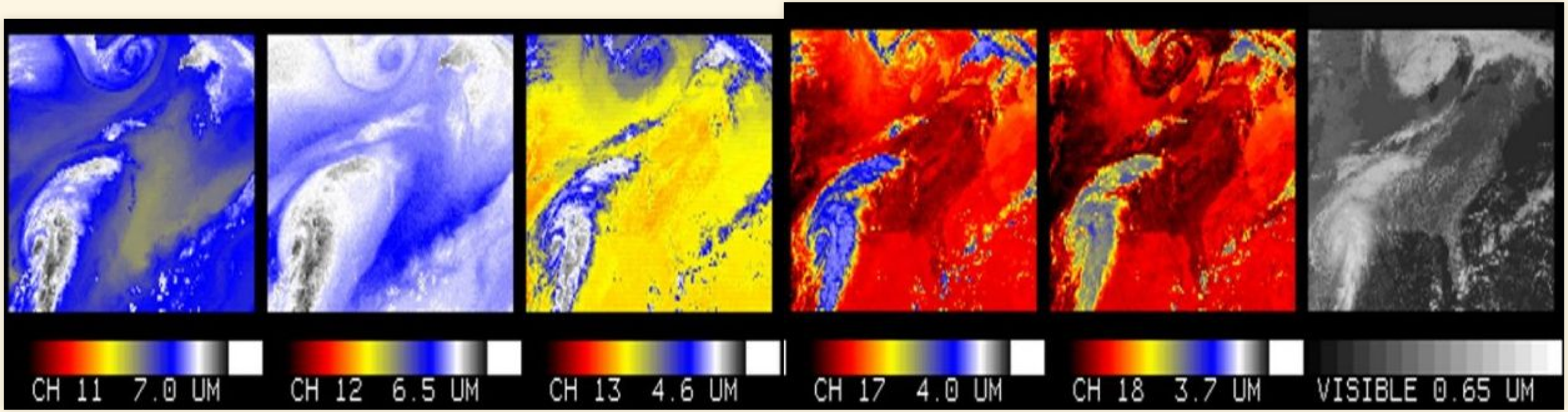
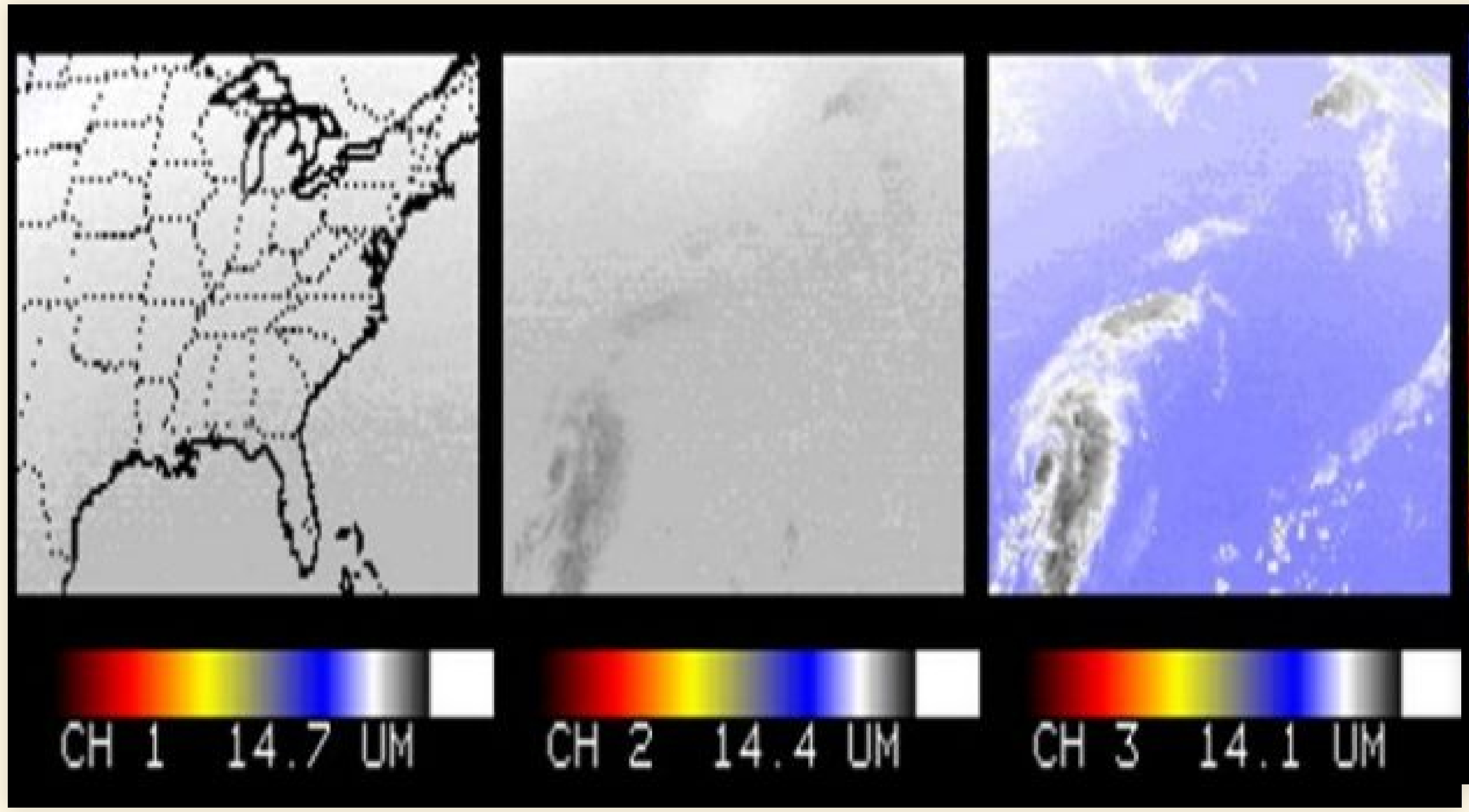
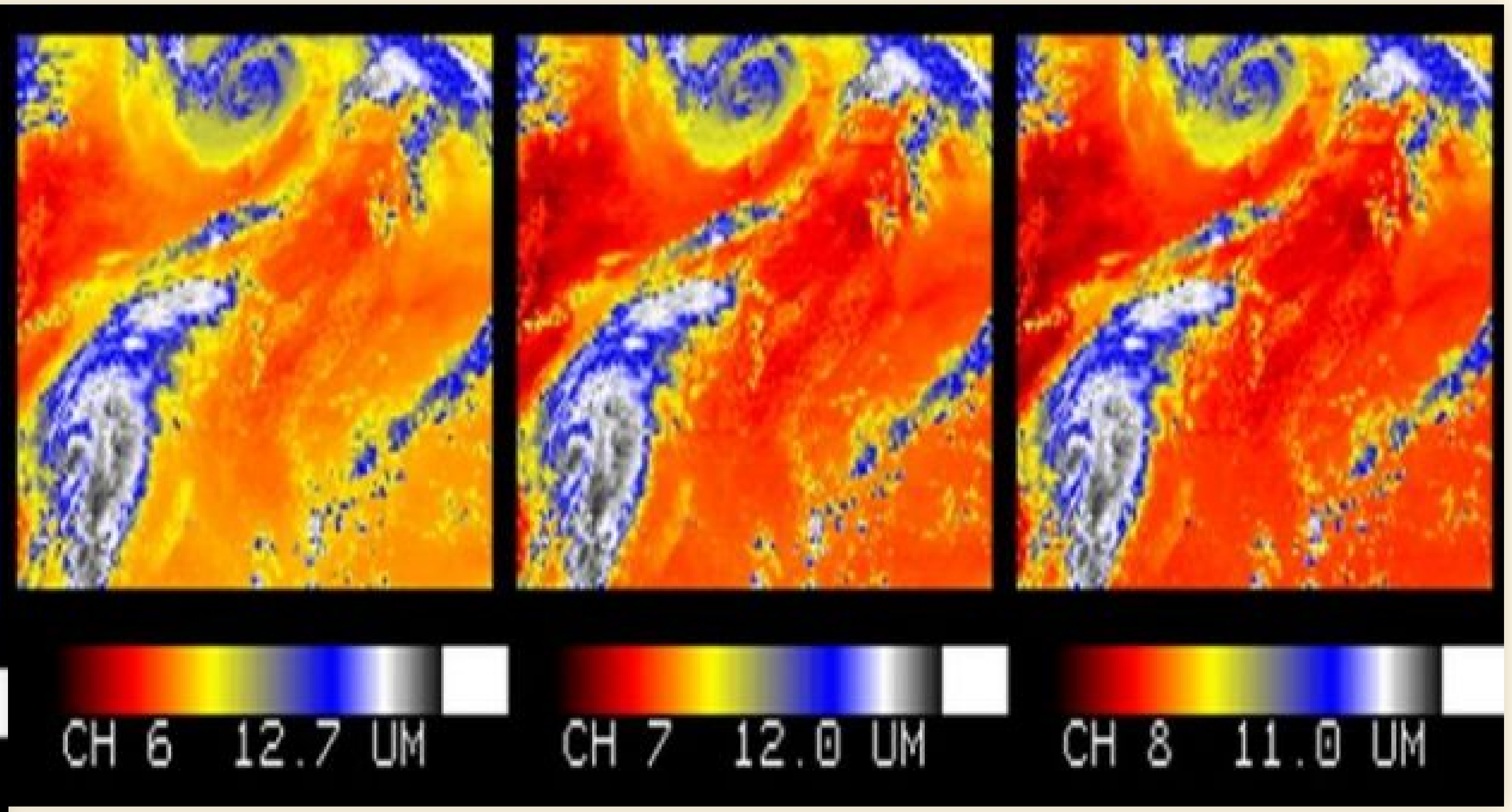
Water, Window, Visible



CO_2 peak vs. Window





Terrestrial Planets

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
Albedo	0.30	0.17	0.71
$T_{\text{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K

Vocabulary note:

- "radiative temperature"
- "skin temperature"
- "bare rock temperature"

all mean the same thing.

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
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$T_{\text{radiative}}$	$254\ \mathrm{K}$	$216\ \mathrm{K}$	$240\ \mathrm{K}$
Actual T_{surface}	$295\ \mathrm{K}$	$240\ \mathrm{K}$	$700\ \mathrm{K}$
One-Layer T_{surface}	$302\ \mathrm{K}$	$257\ \mathrm{K}$	$286\ \mathrm{K}$
Difference	$7\ \mathrm{K}$	$17\ \mathrm{K}$	$-414\ \mathrm{K}$

One-layer model works pretty well for Earth.

Not so well for Mars

Terribly for Venus.

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
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One-Layer T_{surface}	$302\ \mathrm{K}$	$257\ \mathrm{K}$	$286\ \mathrm{K}$
Difference	$7\ \mathrm{K}$	$17\ \mathrm{K}$	$-414\ \mathrm{K}$
Atmospheric pressure at surface	$1013\ \mathrm{mb}$	$6\ \mathrm{mb}$	$92{,}000\ \mathrm{mb}$